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Unlocking the Social Promise of Industry 5.0: Harnessing Data-Driven Social Life Cycle Assessment for Corporate Sustainability

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ABSTRACT

In the contemporary era of Industry 5.0, characterized by the integration of digital technologies and human-centered approaches, the assessment of social sustainability remains a critical challenge. Corporate responsibility and Environmental, Social, and Governance compliance are being reshaped by these developments. This paper aims to address the gap between industrial development and social impact by exploring the transformative potential of Social Life Cycle Assessment within the stakeholder framework established by the United Nations Environment Program. The proposed methodology is both standardized and data-driven, employing advanced techniques such as Principal Component Analysis and sigmoid normalization to minimize subjectivity and enhance comparability. It is validated through a case study in the Italian ceramic industry, utilizing internal organizational data aligned with Social Organizational Life Cycle Assessment guidelines. The findings highlight the urgent need for reliable, data-driven social impact assessments to support regulatory compliance, strengthen Environmental, Social, and Governance strategies, and foster long-term corporate sustainability. Furthermore, the results demonstrate how integrating Social Organizational Life Cycle Assessment into Industry 5.0 frameworks can improve stakeholder engagement, drive social innovation, and contribute to sustainable business practices.

1 | Introduction

European companies face several barriers to systematically assessing the social sustainability impacts of their operations (Blandino and Montagna 2025). These challenges are multifaceted and include issues related to data availability, resources, regulatory frameworks, and organizational culture. Fragmented and insufficient data, along with the absence of standardized and objective metrics and benchmarks, hinder accurate measurement and reporting of social impacts (Kakogiannis 2024). The intangible, sensitive, and often context-specific nature of social impacts complicates quantification, whereas legal diversity across European countries creates inconsistent conditions for adopting uniform sustainability practices.

Corporate Social Responsibility (CSR) remains largely voluntary in many areas, reducing the enforcement of systematic assessments; organizational resistance to integrating social sustainability further hampers progress. Moreover, unclear stakeholder expectations and limited demand for detailed reporting reduce the perceived need for objective assessments (Paridhi et al. 2024). These challenges are further compounded by fragmented regulatory frameworks, weak stakeholder pressure, and poor integration into corporate governance models, all of which hinder the consistent adoption of social sustainability practices across Europe.

However, despite the EU Corporate Sustainability Reporting Directive (CSRD) mandating the disclosure of social indicators, empirical evidence on its effectiveness in enhancing organizational practices remains limited (Hristov and Searcy 2024). Currently, social sustainability evaluations still rely heavily on subjective assessments due to the lack of formalized evaluation techniques (Walker et al. 2021). For example, social indicators are not fully integrated into corporate decision-making via business intelligence systems, making it difficult to align assessments with broader organizational goals. Moreover, real-time databases built on objective indicators are not yet available to support systematic social sustainability assessments.

In response to these limitations, researchers have increasingly explored how information technology—particularly data analytics and machine learning—can improve the accuracy and reproducibility of social impact assessments (Varriale et al. 2023). Furthermore, recent legislative changes, such as the CSRD (European Commission 2021), emphasize the growing importance of social sustainability in business reporting, requiring companies to disclose non-financial social indicators as part of their broader ESG commitments (Hristov and Searcy 2024).

Previous studies have focused on existing social sustainability assessment frameworks, such as Social Return on Investment (SROI) and Social Impact Assessment (SIA). The SROI framework attributes economic value to social benefits, but it faces major limitations due to the subjectivity of assumptions and the difficulty in monetizing intangible outcomes (Gutiérrez-Nieto et al. 2025). By contrast, the SIA framework provides a holistic and participatory method for evaluating social impacts; yet, it is often complex, poorly standardized, and resource intensive (Alomoto et al. 2022). These frameworks are primarily qualitative and subjective, lacking the reproducibility and standardization required for strategic decision-making (Walker et al. 2021). Even structured tools like Social Life Cycle Assessment (S-LCA) and its organizational variant (SO-LCA) have not yet fully adopted quantitative methods capable of reducing subjectivity and enhancing cross-firm comparability (Gutierrez-Lopez et al. 2023).

Earlier applications of S-LCA in the Life Cycle Assessment domain have largely remained qualitative, context-specific, and methodologically inconsistent, limiting their replicability across sectors and alignment with Industry 5.0 principles or CSRD compliance. For instance, Graham et al. (2024) used participatory methods in a Canadian beef supply chain, relying on interviews, Q-method surveys, and interpretive synthesis to assess social performance, but lacked scalable indicators and cross-sector comparability. van Dulmen et al. (2025) critically evaluated S-LCA frameworks, noting that current methods struggle to establish causal links between social impacts and value-chain behaviors, suffer from ambiguous functional units, redundant indicator sets, and qualitative bias. Moreover, a recent systematic review of S-LCA in the construction sector highlights the use of inconsistent indicators, variable system boundaries, and sector-specific assumptions, leading to methodological fragmentation and limited generalizability of results (Ayassamy and Pellerin 2023).

These studies have also generally failed to address the comprehensive integration of social sustainability into Industry 5.0 frameworks (Santiago et al. 2025); nor have they examined the implications of Corporate Social Responsibility Disclosure (CSRD) on social sustainability initiatives. They lack systematic approaches capable of addressing the unique challenges of Industry 5.0 and of supporting the development of objective, reproducible methods for social sustainability assessment. New quantitative approaches using advanced statistical techniques, such as machine learning algorithms, are needed to ensure objectivity and replicability in these assessments. Therefore, there is a pressing need for robust, standardized methodologies that align with the human-centric principles of Industry 5.0 (Ghobakhloo et al. 2023). This study addresses this gap by enhancing the SO-LCA methodology through the integration of machine learning and data normalization techniques, offering a novel framework that supports both regulatory compliance and human-centered industrial transitions. The need for a comprehensive framework is further reinforced by the growing imperative to regulate social sustainability in manufacturing environments (Papetti et al. 2020).

The aim of this research is to enhance the Social Organizational Life Cycle Assessment (SO-LCA) methodology by integrating a data-driven approach to reduce subjectivity in social sustainability assessments. This integration seeks to overcome the limitations of traditional frameworks and ensure a more transparent, standardized, and reproducible model for corporate sustainability management. By leveraging advanced techniques such as Principal Component Analysis (PCA) and sigmoid normalization, the study proposes a more systematic and objective framework for evaluating social performance. Accordingly, this research addresses the following questions:

RQ1. How can data-driven methodologies improve the objectivity and reproducibility of social sustainability assessments in Industry 5.0?

RQ2. How can the integration of SO-LCA into corporate decision-making frameworks enhance ESG compliance and social responsibility?

The implementation of tools such as Social Life Cycle Assessment (S-LCA) is emerging as a strategic approach in today's data-driven, regulation-intensive business landscape (Gutierrez-Lopez et al. 2023). S-LCA offers a structured framework for assessing social impacts across the life cycle of products, processes, and organizations, addressing key dimensions such as labor conditions, stakeholder relationships, and community engagement (Bouillass et al. 2021).

This study underscores the transformative potential of a data-driven SO-LCA in bridging the gap between social sustainability and Industry 5.0. It offers businesses an objective and scalable approach to assess social impacts, whereas aligning with Life Cycle Thinking (LCT) principles and broader sustainability goals (Mesa Alvarez and Ligthart 2021). A key contribution is the development of a novel methodology that incorporates machine learning algorithms to minimize subjectivity in SO-LCA assessments and enhance comparability across firms, in line with UNEP guidelines. By leveraging advanced data analytics, this research provides firms with transparent and reliable tools for measuring and managing social impacts, thereby fostering a more inclusive and accountable sustainability framework. Furthermore, the study offers valuable insights for both scholars and practitioners aiming to integrate human-centered approaches into sustainability strategies, whereas balancing economic, environmental, and social objectives.

The remaining sections of the paper are organized as follows. The Theoretical Background reviews existing approaches, such as SROI and SIA, and discusses their limitations in assessing social sustainability. The Methodology section presents the hybrid qualitative–quantitative framework, justifies the case study selection, and outlines how SO-LCA has been adapted to the Industry 5.0 context. The Data Analysis and Results section provides empirical findings on social impacts derived from the revised SO-LCA approach. Finally, the Interpretation and Discussion sections examine the theoretical and practical implications of the results considering Industry 5.0 and the EU CSRD, followed by Conclusions that summarize key contributions, acknowledge limitations, and propose future research directions.

2 | Theoretical Background

2.1 | Exploring Social Sustainability Frameworks

The integration of diverse perspectives and needs relies on the consideration of stakeholder views regarding sustainable development and social relations as fundamental components (Colasante et al. 2024). The overarching objective is to promote equitable well-being (D'Adamo et al. 2024). Literature has explored a wide range of models to assess social sustainability, encompassing qualitative, quantitative, and mixed-method approaches (Govindan et al. 2021). Among these, several prominent frameworks offer distinct methods for evaluating the social dimension of sustainability (Ikram et al. 2020). One notable quantitative approach is Social Return on Investment (SROI), which assigns economic value to the social outcomes generated by an organization's activities (Ariza-Montes et al. 2021). SROI provides stakeholders with a monetized metric to assess social impact by comparing the benefits created with the investment required. Its process typically involves: (1) identifying relevant stakeholders, (2) mapping outcomes, (3) evaluating the effects, and (4) calculating the total social value generated (Nikolakis and da Veiga 2023). In contrast, Social Impact Assessment (SIA) offers a comprehensive framework for evaluating the social effects of proposed projects, policies, or regulations (Corvo et al. 2021). SIA captures both positive and negative impacts across multiple dimensions—economic, cultural, and environmental—by applying a mix of qualitative and quantitative tools. Its main goal is to support decision-making by identifying potential risks and opportunities for affected communities (Stjernborg 2023).

2.2 | Life Cycle Approaches: S-LCA and SO-LCA

Methodologies that systematically assess the social impacts of goods, services, or organizations across their life cycle—or within internal processes—include Social Life Cycle Assessment (S-LCA) and Social Organizational Life Cycle Assessment (SO-LCA) (D'Eusanio et al. 2022a). S-LCA extends the traditional Life Cycle Assessment (LCA) framework beyond environmental aspects to incorporate social concerns such as working conditions, human rights, and community engagement. It offers a comprehensive view of social impacts across the product life cycle, using both qualitative and quantitative indicators (Tokede and Traverso 2020). SO-LCA, by contrast, focuses on organizational-level assessment, capturing social aspects related to employee well-being, diversity, and stakeholder involvement (D'Eusanio et al. 2022b). A defining feature of both methods is their capacity to support the integration of social sustainability into corporate decision-making, helping firms align operational practices with broader sustainability goals (Huertas-Valdivia et al. 2020).

2.3 | Challenges in Social Sustainability Assessment

Although S-LCA and SO-LCA offer valuable support, significant implementation challenges persist. First, the lack of standardization leads to inconsistent protocols and divergent results across assessments (Mulloth and Rumi 2022). Second, the inherent subjectivity in data collection and analysis compromises the reliability and objectivity of results (Zheng et al. 2020). Additionally, nonstandardized documentation and methodological heterogeneity undermine the replicability of findings (Kalvani et al. 2021). Comparability is also a major concern due to variability in frameworks, indicators, and metrics. Moreover, manual data collection and analysis hinder scalability and increase the risk of error and inefficiency (Czaja-Cieszyńska et al. 2021). To address these issues, integration of social assessment models into organizational decision-making is essential (Walker et al. 2021). Leveraging business intelligence (BI) systems can bridge the gap between strategy and operations, improving alignment with ESG goals and enhancing the precision of social impact measurement (Karthik et al. 2025). Effective strategies include standardization, automation, enhanced objectivity, repeatability, and full integration into digital decision-making systems. Overcoming these barriers will enable companies to embed social sustainability evaluations into core processes and drive meaningful, long-term transformation.

2.4 | The Role of Regulatory Frameworks

The EU Corporate Sustainability Reporting Directive (CSRD) marks a major shift in the regulatory landscape, introducing stricter reporting obligations and greater transparency in corporate sustainability practices within the European Union (EU) (Richter et al. 2023). It significantly redefines expectations around environmental, social, and governance (ESG) accountability, requiring companies to disclose comprehensive nonfinancial information, including social indicators, in their annual reports (Arvidsson and Dumay 2022). Importantly, the CSRD extends its scope beyond individual firms to include their entire supply networks, underscoring the need for robust mechanisms to assess and monitor social risks across the value chain (Kilian-Yasin and Correa 2021; Villiers 2022). From raw material suppliers to end users, this expansion reinforces the imperative to regulate social sustainability throughout all supply chain tiers. As a result, there is a growing demand for effective tools and methodologies to conduct systematic social assessments, enabling companies to identify, track, and mitigate risks related to social performance (Lafarre 2023). By aligning with the goals of the CSRD (Samagaio and Diogo 2022), companies can ensure compliance while generating positive social impact across their operations and supplier ecosystems. Given this evolving legal context, adopting robust, data-driven approaches to manage social sustainability is no longer optional; it is a strategic necessity.

In this context, the application of Life Cycle Thinking (LCT) technologies is becoming increasingly critical to assess and minimize social impacts across the supply chain (Mohammad Ebrahimi and Koh 2021). Social Life Cycle Assessment (S-LCA) (Luthin et al. 2023) and Social Organizational Life Cycle Assessment (SO-LCA) (García-Muiña et al. 2021) provide structured methods for integrating social analysis within broader frameworks such as Life Cycle Assessment (LCA) (Kokare et al. 2023) and Organizational Life Cycle Assessment (O-LCA) (Cucchi et al. 2023) used for environmental performance. Integrating S-LCA and SO-LCA with conventional LCA and O-LCA tools enables businesses to adopt a comprehensive sustainability evaluation approach that aligns with CSRD requirements. This unified framework facilitates the identification of synergies and trade-offs between social and environmental goals, promoting more informed and integrated decision-making (Fernhaber and Hawash 2023). As regulatory pressure and stakeholder expectations intensify, the adoption of LCA-based techniques—particularly S-LCA and SO-LCA—is emerging as a strategic enabler of responsible governance and sustainability leadership (Mancini et al. 2023).

2.5 | Integrating Industry 5.0 and SO-LCA

The shift from Industry 4.0 to Industry 5.0 marks a significant evolution in industrial paradigms—moving beyond automation and efficiency toward greater emphasis on social sustainability, human-centricity, and ethical governance (Golovianko et al. 2023). Although Industry 4.0 prioritized digital automation and connectivity, it often neglected social and environmental dimensions. In contrast, Industry 5.0 integrates advanced technologies with inclusive and sustainable practices, centering on the human role in production (FengTang and Leong 2024). This paradigm promotes collaboration between humans and machines to enhance human capabilities, fostering flexible industrial environments that emphasize trust, engagement, and teamwork. These characteristics are closely linked to Sustainable Human Resource Management (SHRM), a key enabler of social sustainability (Sołtysik et al. 2024). Industry 5.0 also incorporates ESG principles, aligning with global sustainability goals by advancing ethical governance and reducing ecological impacts through AI, IoT, and blockchain technologies (Chandre et al. 2024; Rehman and Umar 2025). In this context, Social Life Cycle Assessment (S-LCA) aligns naturally with Industry 5.0 values, offering a structured method for assessing and improving social performance (Panza et al. 2023). Its organizational extension, SO-LCA, leverages data analytics and big data to measure social parameters objectively and consistently across sectors (García-Muiña et al. 2022). This enables firms to embed ethical principles into operations, ensuring economic viability, environmental sustainability, and social equity. Moreover, the ethical deployment of technology—a cornerstone of Industry 5.0—reinforces alignment with societal values and privacy protections (Barata and Kayser 2023). Transitioning to Industry 5.0 requires a redefinition of industrial frameworks to accommodate these human-centered and sustainability-oriented practices (Zizic et al. 2022). SO-LCA contributes to this transition by delivering actionable insights on social performance, strengthening CSR in the digital era (Kumari and Singh 2023). In doing so, SO-LCA transcends the efficiency-centric limitations of Industry 4.0, paving the way for a more inclusive and responsible industrial ecosystem.

2.6 | Industry 5.0 and the Imperative of Social Responsibility

The convergence of advanced digital technologies and human-centered principles in Industry 5.0 represents a fundamental transformation in manufacturing paradigms—one that emphasizes human capital, social well-being, and ethical responsibility (Ivanov 2023). In this context, the obligations introduced by the EU CSRD reinforce the need for businesses to assess and manage the social impacts of their operations. Unlike previous industrial revolutions, which focused on productivity and efficiency, Industry 5.0 prioritizes inclusive growth, employee empowerment, and ethical practices across the value chain (Atif 2023). As a result, manufacturers are under increasing pressure to evaluate their labor practices, diversity, workplace well-being, and community engagement (Alojaiman 2023). Embedding social responsibility into business strategies has been shown to strengthen brand reputation, stakeholder trust, innovation capacity, and long-term value creation (Torres de Oliveira et al. 2023). In parallel, CSRD regulations require a systematic and transparent approach to assessing and communicating social performance (Ortiz-Martínez et al. 2023). The alignment between Industry 5.0 and CSRD highlights the growing awareness of the interdependence between corporate activity and societal well-being. This convergence calls on companies to treat social responsibility not as a secondary concern, but as a strategic pillar of industrial transformation (Asif et al. 2023).

3 | Methodology

This research proposes a mixed-method approach, revising the SO-LCA methodology to enhance objectivity in social sustainability assessments within the manufacturing sector. By integrating Industry 5.0 principles and advanced data-driven models, the new methodology aims to reduce the subjectivity typically found in traditional SO-LCA methods, which often rely on qualitative data. The proposed methodology is structured in accordance with the ISO 14044 framework, traditionally applied in environmental assessments. This framework includes goal and scope definition, inventory analysis, impact assessment, and interpretation. Although aligned with UNEP guidelines, the revised approach introduces quantitative processes to improve comparability across companies. This structured design clarifies the social sustainability assessment and supports its application in various industrial contexts.

To ensure consistency and comparability, the methodology applies two advanced quantitative techniques: Sigmoid Normalization and Principal Component Analysis (PCA). Sigmoid normalization was selected for its ability to scale data within a bounded range (0–1) while maintaining the proportional relationships between values. Unlike min–max scaling, which can be heavily influenced by outliers, sigmoid normalization minimizes such effects, producing balanced transformations across indicators. For example, workplace safety data (e.g., incident rates) and community engagement metrics (e.g., number of initiatives) were normalized using the sigmoid function, ensuring cross-indicator consistency despite differences in scale or units. PCA was chosen to address dimensionality reduction while preserving the most relevant information in the dataset. By grouping correlated variables into principal components, PCA reduces redundancy and reveals underlying patterns. In contrast to manual weighting or expert judgment, PCA provides an objective, data-driven weighting mechanism, enhancing reproducibility and transparency.

During the data collection phase, indicators such as safety records, stakeholder engagement, and supplier performance were collected from multiple sources, including employee surveys and supplier audits. These raw data points were first normalized using the sigmoid function to ensure comparability. Then, PCA was applied to aggregate them into composite indices, such as Worker Well-being and Community Development. This approach streamlined the evaluation process and delivered actionable insights by identifying priority areas for improvement. The efficacy of the revised methodology was tested through a case study of a leading Italian ceramic tile manufacturer, known for its Industry 5.0 initiatives and its experience with environmental assessments through ERP systems. This company served as an ideal test case to validate the new approach. The case study demonstrated the methodology's potential to bridge the gap between social and environmental sustainability evaluations, offering a more integrated and objective assessment.

Given the current lack of primary social data, this research initially combines the quantitative model with expert committee input based on prior studies (García-Muiña et al. 2021). However, as more companies adopt this framework and contribute data, the long-term goal is to develop a fully quantitative, standardized model for social sustainability assessment—thereby reducing reliance on subjective inputs.

4 | Results

This section provides a step-by-step guide to implementing the revised SO-LCA methodology, particularly in the context of the manufacturing sector. The structure follows the four standard phases of the ISO 14044 framework: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. The proposed approach introduces innovative techniques while remaining aligned with UNEP guidelines, offering a more detailed and accurate representation of social sustainability performance.

4.1 | Goal and Scope Definition

The methodology was applied across three production facilities and the headquarters of a ceramic tile manufacturing company. The adoption of digital technologies in manufacturing and business operations enabled the collection of primary social data in real time. In line with UNEP's SO-LCA framework, the reporting organization was defined using a "cradle-to-grave" system boundary, serving as the unit of analysis.

Stakeholder identification and classification followed UNEP's six stakeholder categories and four impact categories, with flexibility to adjust based on specific value chain needs. In this study, the stakeholder groups included: workers, local communities, society, consumers, and value chain actors. The children category was excluded, as it was not relevant to the company's supply chain. Stakeholders were selected based on their relevance within the firm's operational value chain, enabling the evaluation of effects through primary data-driven social metrics. The impact categories adopted align with sustainable capital theory, encompassing human, social, natural, and economic capital. Subcategories were generated in accordance with the UNEP SO-LCA methodological guidelines. In particular, the "Environment" subcategory under the Society stakeholder group allowed for a direct link to parallel environmental assessments. Table 3 presents the Industry 5.0–based stakeholder classification and corresponding effect categories used in the study.

4.2 | Inventory Analysis

The use of digital technologies to automatically aggregate data from both headquarters and production sites enables the implementation of an Industry 5.0–based inventory analysis within the SO-LCA program. The ERP system functions as the technical hub, collecting real-time production and management data, which is then connected to a Business Intelligence (BI) platform interfacing with the SO-LCA calculation tool (Figure 1). This integration between digital and physical systems facilitates real-time monitoring of social impacts. Although the model is especially suitable for digitally mature firms, it can also be adapted for organizations still relying on conventional analog data collection, thus supporting gradual digitalization. The combination of ERP, BI, and Industry 5.0 technologies enables cloud-based dynamic inventory analysis (DIA), allowing for continuous, real-time social performance evaluation.

The DIA process begins with the identification of measurable social indicators that are contextually relevant and feasible for primary data collection. A technical-scientific committee selected these indicators by developing a correlation matrix that links stakeholder categories to their corresponding impact domains. For instance, indicators such as collective bargaining agreements

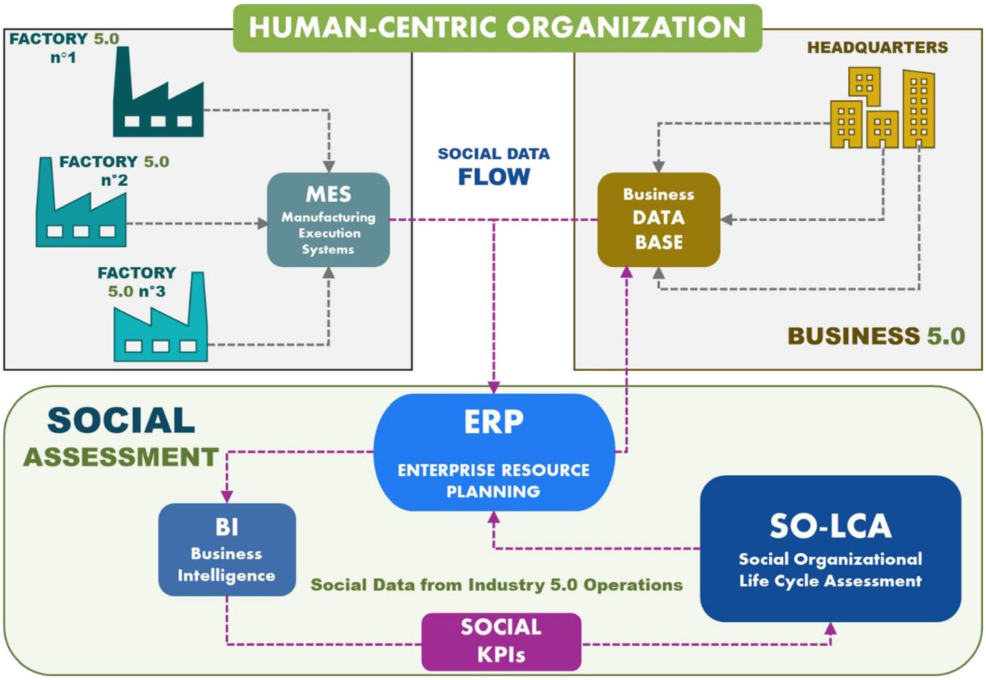

FIGURE 1 | Data-driven social organizational life cycle assessment, adapted from García-Muiña et al. (2022).

(CBAs) and the provision of personal protective equipment (PPE) are associated with workers and relate to human capital impacts. Likewise, interactions with local governments and community stakeholders serve as metrics for local communities within the domain of social capital, whereas measures like research and innovation hours and regulatory participation are used to capture broader societal impacts aligned with natural and social capital. Additionally, revenue generated and non-compliance costs are included to reflect the perspective of consumers and value chain actors. Altogether, the inventory analysis incorporates 46 company-specific social indicators, which are aggregated into 28 Dynamic Social Indicators (DSIs). These DSIs enable a clear classification of the organization's social impacts as either positive or negative, as presented in Table 1.

4.3 | Context-Aware Social Impact Assessment

The impact assessment method establishes a hierarchical structure that links individual social indicators to two levels of evaluation: impact subcategory indices (midpoints) and impact category indices (endpoints). This framework allows for a comprehensive measurement of how the organization's operations affect various stakeholder groups. The analysis is based on 46 social indicators, systematically organized into 28 Dynamic Social Indicators (DSIs). These indicators, collected between 2021 and 2023 (see Table 4), form the foundation of a structured and replicable assessment framework. Each indicator is evaluated in terms of whether increases or decreases in its value represent a positive or negative social effect, enabling a clear and actionable interpretation of results.

In line with dynamic Life Cycle Assessment (LCA) principles, this phase of the analysis focuses on processing the DSI ratios to determine their contributions to midpoint and endpoint scores for each impact subcategory and category. Data is scaled and quantified objectively, with each indicator weighted according to its relative importance within its corresponding impact dimension. These results are then integrated into a consolidated Dynamic Sustainability Index, offering a comprehensive and robust metric for evaluating overall social sustainability performance. The final index highlights key strengths and opportunities for improvement, supporting strategic decision-making and stakeholder communication.

Accurate interpretation and comparison of multiple indicators require scaling procedures that maintain the intrinsic structure of the data. Two commonly used approaches are data normalization (adjusting values to a mean of zero and standard deviation of one) and min–max standardization (scaling values to a 0–1 range). Although normalization supports direct comparison, it can complicate aggregation due to value heterogeneity (Gee et al. 1997). In contrast, min–max standardization simplifies interpretation but is vulnerable to outliers, potentially leading to misleading conclusions, especially in small datasets. To address these limitations, the methodology adopts a hybrid transformation: normalization followed by sigmoid scaling, a logarithmic function that bounds values between 0 and 1. This method preserves significant variation in the original data while reducing the influence of extreme values, making it particularly suitable for social sustainability studies, where datasets may be limited and indicator variability high. This integrated approach combines the strengths of both normalization and standardization, offering a balanced and robust solution for ensuring accurate and meaningful indicator comparisons (Allen et al. 2021). The mathematical transformation used in this method is presented below:

$$\sigma\left(\frac{x-\mu}{\sigma}\right) = \frac{1}{1+e^{\left(\frac{x-\mu}{\sigma}\right)}}$$

TABLE 1 | Dynamic inventory analysis data base.

Stakeholder categories	Impact categories	Stakeholder subcategories	Impact subcategories	Dynamic social indicators		Indicators description by metrics	Social positive influence
1. Workers	A. Human capital	1.1 Staff personnel	A1. Human rights	DSI-A1.1	Gender equality	(No. of women)/(total workforce)	INCREASE
				DSI-A1.2	Childhood workforce	(No. of children)/(total workforce)	DECREASE
				DSI-A1.3	Forced labour	(No. of forced labor workers)/(total workforce)	DECREASE
				DSI-A1.4	Migrant worker	(No. of migrant workers)/(total workforce)	INCREASE
			A2. Health and safety	DSI-A2.1	Lost time injury frequency rate (LTIFR)	(NO. of injuries x 1,000,000) / (Hours worked)	DECREASE
				DSI-A2.2	Personal protective equipment (PPEs)	(No. of PPEs)/(total workforce)	INCREASE
		1.2 Trade unions	A3. Working conditions	DSI-A3.1	Collective bargaining agreement (CBA)	(No. CBA)/(total workforce)	INCREASE
				DSI-A3.2	Overtime working hours	(Man-hours overtime)/(hours worked)	DECREASE
				DSI-A3.3	Full-time staff	(Full-time staff)/(total workforce)	INCREASE
				DSI-A3.4	Local workforce	(Local workforce)/(total workforce)	INCREASE
				DSI-A3.5	Training	(Training hours)/(hours worked)	INCREASE
2. Local community	B. Social capital	2.1 Local institutions	B1. Local expectations	DSI-B1.1	Stakeholders engagement	(Stakeholders engaged/stakeholders mapped)	INCREASE
				DSI-B1.2	Public engagement	(Local governments engaged/No. local governments)	INCREASE
3. Society		3.1 Public and private organizations	B2. Institutional expectations	DSI-B2.1	University engagement	(Man-hours of scientists)/(Man-hours into R&D&I)	INCREASE
				DSI-B2.2	Regulatory authorities engagement	(Authorities engaged)/(No. of regulatory authorities)	INCREASE

(Continues)

TABLE 1 | (Continued)

Stakeholder categories	Impact categories	Stakeholder subcategories	Impact subcategories	Dynamic social indicators		Indicators description by metrics	Social positive influence
		3.2 Media	B3. Corporate reputation	DSI-B3.1	Corporate social media engagement	(Corporate followers/ corporate likes)	INCREASE
				DSI-B3.2	B2B social media engagement	(B2B followers/B2B likes)	INCREASE
				DSI-B3.3	B2C social media engagement	(B2C followers/B2C likes)	INCREASE
	C. Natural capital	3.3 Environmental	C1. Carbon footprint	DSI-C1.1	Global warming potential (GWP)	(Company GWP/industry GWP)	DECREASE
4. Consumers	D. Economic capital	4.1 Trade channel operators	D1. Customer expectations	DSI-D1.1	B2B non-compliance	(B2B non-compliance costs)/(B2B turnover)	DECREASE
		4.2 Final consumer		DSI-D1.2	B2C non-compliance	(B2C non-compliance costs)/(B2C turnover)	DECREASE
5. Value chain actors		5.1 Private business	D2. Private expectations	DSI-D2.1	HR-based R&D workforce	(Researchers staff)/ (total workforce)	INCREASE
				DSI-D2.2	HR-based innovation workforce	(Innovators staff)/ (total workforce)	INCREASE
				DSI-D2.3	R&D & innovation	(R&D&I. invest.)/(total invest.)	INCREASE
		5.2 Suppliers	D3. Ethical behavior	DSI-D3.1	Order approval manager	(No. of approved orders/ No. of total orders)	INCREASE
				DSI-D3.2	Ethical key suppliers	(Ethical key suppliers/ total key suppliers)	INCREASE
				DSI-D3.3	Local suppliers	(Local suppliers/total suppliers)	INCREASE
				DSI-D3.4	Local suppliers turnover	(Local suppliers turnover/ key suppliers turnover)	INCREASE

where x is the input value to be standardized and transformed. μ is the mean of the dataset, which helps center the data around 0. σ is the standard deviation of the dataset, which scales the data so that it has a unit variance. $\left(\frac{x-\mu}{\sigma}\right)$ represents the sigmoid function applied to the standardized value of x.

The weighting of indicators enables their aggregation into corresponding Dynamic Social Indices (DSIs), ultimately allowing the calculation of a composite dynamic sustainability index. To facilitate this, dimensionality reduction techniques are employed to consolidate original indicators into impact indexes that better reflect their underlying behavior. Within the Life Cycle Thinking framework, common weighting approaches include equal weighting, expert judgment, and the Analytic Hierarchy Process (AHP) (Alyami et al. 2015). However, these methods are inherently subjective, often shaped by personal preferences or contextual biases.

To overcome this limitation, the methodology employs Principal Component Analysis (PCA)—a robust statistical technique that reduces dimensionality while retaining the most informative variation in the data. PCA provides an objective, analytical basis for weighing and aggregating indicators. By applying PCA to each effect category and extracting the first principal component (PC1), the model derives a polynomial that reflects the relative variability contributed by each indicator (Mohsine et al. 2023). PC1 is computed as a linear combination of the original indicators, where each variable is multiplied by a coefficient corresponding to its informative weight. These PC1 scores serve as the composite index for each social impact category and are used to weigh and aggregate indicators in a scientifically grounded manner. This approach ensures maximum information retention while minimizing subjective bias in index construction.

The analytical workflow was implemented using R programming language, through a custom-built script specifically designed to meet the requirements of this study. The process began by dividing the dataset according to impact categories. Then, aggregate weights for each indicator were computed using the prcomp() function (Settanni 2024) to extract the PC1 coefficient vector. An ad hoc function was used to rescale the coefficients, ensuring that all weights were positive and summed to one. The next step involved scaling the database using a sigmoid transformation, preceded by normalization to standardize the indicator values. A custom function applied the sigmoid scaling to each indicator. Finally, the scaled data was multiplied by the weight vectors, resulting in a complete matrix representing each social effect index. This procedure was then repeated using PCA on the full matrix of effect category indexes, enabling the computation of the global social sustainability index. A detailed mathematical representation of this PCA-based process is provided in Table 2.

4.4 | Interpretation of Assessment Results

This section presents the results of the Social Organizational Life Cycle Assessment (SO-LCA) and focuses on two main components. First, it analyzes the weighting and aggregation of Dynamic Social Indicators (DSIs) using a mixed-method

TABLE 2 | Principal component analysis process applied to sustainable index definition.

Step 1: Calculating the first principal component (PC1)

Given a set of social indicators $X = [x_1, x_2, \ldots, x_n]$ where each x_i represents an indicator and n is the total number of indicators, PCA transforms this set into principal components.
The first principal component (PC1) is calculated by finding the vector of coefficients $a = [a_1, a_2, \ldots, a_n]$ that maximizes the variance of X projected onto a subject to $\|a\| = 1$. This can be formulated as the optimization problem:
$\max_a Var(Xa)$ subject to $\|a\|^2 = 1$

Step 2: Representation of PC1

PC1 is represented as the weighted sum of the original indicators by their coefficients:
$PC1 = a_1x_1 + a_2x_2 + \ldots + a_nx_n$
This can be expressed in matrix form as $PC1 = Xa$.

Step 3: Weighting the coefficients

To ensure the coefficients are positive and sum to one, we perform a normalization:
$a'_i = \frac{|a_i|}{\sum_{k=1}^{n} |a_k|}$
This transforms each a_i coefficient into a weight a'_i for the corresponding indicator, ensuring all weights are positive and their sum equals 1.

Step 4: Calculating the social impact index

Finally, the value of the social impact index for a category j is calculated by multiplying each indicator by its weighted coefficient and summing the results:
$$\text{Index}_j = \sum_{i=1}^{n} a'_i x_i$$
This provides an aggregated value or Index that represents the impact of category j that retains most of the original variability, considered as the information provided by each indicator.

TABLE 3 | Weighting criteria of dynamic social indicators DSI and impact subcategories.

Dynamic social indicators	Indicator weight			Impact subcategories	Index weight			Impact categories
	Experts	PCA	Mixed		Experts	PCA	Mixed	
Gender equality	20%	50.0%	35.0%	Human rights	30%	41.4%	35.7%	Human capital
Childhood workforce	35%	0.0%	17.5%					
Forced labour	35%	0.0%	17.5%					
Migrant worker	10%	50.0%	30.0%					
Lost time injury frequency rate (LTIFR)	80%	50.0%	65.0%	Health and safety	30%	46.8%	38.4%	
Personal protective equipment (PPEs)	20%	50.0%	35.0%					
Collective bargaining agreement (CBA)	30%	0.0%	15.0%	Working conditions	40%	11.8%	25.9%	
Overtime working hours	10%	25.5%	17.7%					
Full-time staff	20%	24.2%	22.1%					
Local workforce	20%	25.1%	22.6%					
Training	20%	25.1%	22.6%					
Stakeholders engagement	60%	100.0%	80.0%	Local expectations	30%	26.4%	28.2%	Social capital
Public engagement	40%	0.0%	20.0%					
University engagement	60%	50.0%	55.0%	Institutional expectations	20%	35.5%	27.7%	
Regulatory authorities engagement	40%	50.0%	45.0%					
Corporate social media engagement	25%	39.8%	32.4%	Corporate reputation	50%	38.2%	44.1%	
B2B social media engagement	30%	24.9%	27.4%					
B2C social media engagement	45%	35.3%	40.1%					
Global warming potential (GWP)	100%	100.0%	100.0%	Carbon footprint	100%	100%	100%	Natural capital
B2B non-compliance	50%	50.0%	50.0%	Customer expectations	40%	42.1%	41.1%	Economic capital
B2C non-compliance	50%	50.0%	50.0%					
HR-based R&D workforce	20%	33.5%	26.7%	Private expectations	30%	32.7%	31.3%	
HR-based innovation workforce	20%	33.3%	26.6%					
R&D & innovation	60%	33.2%	46.6%					
order approval manager	30%	34.1%	32.0%	Ethical behavior	30%	25.2%	27.6%	
Ethical key suppliers	20%	32.1%	26.0%					
Local suppliers	25%	1.2%	13.1%					
Local suppliers turnover	25%	32.7%	28.9%					

approach that combines expert consultation with Principal Component Analysis (PCA). This integrated methodology supports a more balanced and objective evaluation of social performance by reconciling expert knowledge with data-driven insights. The section also discusses the challenges posed by limited data availability and variability in certain indicators, which can affect result interpretation.

Table 3 presents the weighting values assigned to each DSI and its corresponding impact subcategory. Final weights result from the combined application of qualitative expert judgment and PCA-derived quantitative scores. Although general alignment between expert input and PCA outcomes was observed, some adjustments were necessary. For example, expert consultation emphasized the relevance of indicators related to child labor

TABLE 4 | Social organizational assessment indexes values.

Dynamic social indicators	2021	2022	2023	Impact subcategories	2021	2022	2023	Impact categories	2021	2022	2023
Gender equality	0.499	0.501	0.500	Human rights	0.4998	0.5004	0.4998	Human capital	0.503	0.498	0.499
Childhood workforce	0.500	0.500	0.500								
Forced labour	0.500	0.500	0.500								
Migrant worker	0.500	0.500	0.500								
Lost time injury frequency rate (LTIFR)	0.513	0.491	0.496	Health and safety	0.5083	0.4944	0.4973				
Personal protective equipment (PPEs)	0.499	0.500	0.500								
Collective bargaining agreement (CBA)	0.500	0.500	0.500	Working conditions	0.4997	0.4998	0.5005				
Overtime working hours	0.500	0.500	0.500								
Full-time staff	0.499	0.499	0.502								
Local workforce	0.499	0.500	0.501								
Training	0.500	0.500	0.500								
Stakeholders engagement	0.497	0.503	0.500	Local expectations	0.4978	0.5021	0.5001	Social capital	0.443	0.499	0.558
Public engagement	0.500	0.500	0.500								
University engagement	0.467	0.467	0.565	Institutional expectations	0.4521	0.4857	0.5621				
Regulatory authorities engagement	0.434	0.508	0.558								
Corporate social media engagement	0.330	0.580	0.595	Corporate reputation	0.4019	0.5053	0.5916				
B2B social media engagement	0.388	0.388	0.713								
B2C social media engagement	0.469	0.526	0.505								
Global warming potential (GWP)	0.503	0.496	0.501	Carbon footprint	0.5030	0.4959	0.5011	Natural capital	0.503	0.496	0.501
B2B non-compliance	0.500	0.500	0.500	Customer expectations	0.5000	0.4999	0.5001	Economic capital	0.498	0.501	0.501
B2C non-compliance	0.500	0.500	0.500								
HR-based R&D Workforce	0.500	0.500	0.500	Private expectations	0.4958	0.5002	0.5040				
HR-based innovation workforce	0.499	0.500	0.501								
R&D & innovation	0.491	0.501	0.508								
Order approval manager	0.503	0.498	0.499	Ethical behavior	0.4980	0.5041	0.4979				
Ethical key suppliers	0.480	0.522	0.498								
Local suppliers	0.500	0.501	0.499								
Local suppliers turnover	0.508	0.496	0.496								

and migrant workers, but PCA assigned them lower weights due to the limited variability in the data. Some impact areas, such as Stakeholder Engagement and Public Engagement for Local Expectations, exhibited homogeneous results, reflecting low variation across the dataset. Nevertheless, the fusion of both methods created a more balanced and defensible aggregation strategy, mitigating the weaknesses inherent in either approach used independentl.

Table 4 presents the social indicator values at the organizational level, along with their aggregation across 10 subcategories and four final impact categories. Interestingly, many indicators values cluster around 0.5, which can be explained by three factors: (1) the company-specific reference values used for benchmarking; (2) the sigmoid normalization function, which typically centers values around 0.5; and (3) the consistency of indicator performance over the three-year data collection period. As more organizations contribute to this dataset, the model's comparative robustness and benchmarking potential will increase, enhancing the generalizability of the findings.

The findings confirm that integrating expert opinion and PCA enables a more nuanced and methodologically rigorous SO-LCA evaluation. Although expert judgment highlights strategic issues, PCA reinforces objectivity and transparency by basing weightings on statistical variability. Despite current limitations in dataset size and indicator volatility, the combined approach improves the reliability of social impact assessments. As the model evolves with additional data contributions, its capacity to generate accurate, actionable, and replicable results will strengthen, offering practical value for organizational decision-making.

This revised methodology also leads to the development of a conceptual model (Figure 2) that links the European Corporate Sustainability Reporting Directive (CSRD), the principles of Industry 5.0, and the strategic role of SO-LCA in promoting social sustainability within manufacturing ecosystem.

Figure 2 illustrates how the CSRD, as a regulatory framework, serves as the foundation for advancing social sustainability under the Industry 5.0 paradigm. It mandates rigorous reporting on social dimensions, such as decent work conditions and human rights, whereas encouraging standardized metrics for cross-industry comparability. In contrast, Industry 4.0, with its emphasis on efficiency and automation, often lacks mechanisms to address social impacts, resulting in missed opportunities to mitigate systemic inequalities across global value chains. In response, Industry 5.0 emerges as a paradigm shift that centers on human well-being, ethical responsibility, and the productive use of digital technologies for societal benefit. It explicitly integrates social objectives into manufacturing design, empowering firms to align technological innovation with human-centered values. By emphasizing worker welfare, expanded stakeholder engagement, and data-driven governance, Industry 5.0 paves the way toward a more inclusive and resilient production system.

The model highlights how SO-LCA bridges the gap between these two dimensions. It provides a structured, data-driven means to evaluate social performance, satisfy CSRD obligations, and embed Industry 5.0 criteria into corporate sustainability strategies. SO-LCA thus functions as both a diagnostic tool and a regulatory compliance mechanism, supporting companies in translating abstract policy mandates into concrete, measurable practices.

Overall, the integration of SO-LCA, Industry 5.0, and CSRD—as captured in the conceptual model—offers a strategic roadmap for manufacturers seeking to move beyond the limitations of Industry 4.0 and embrace a new paradigm of sustainable, equitable, and ethically grounded industrial development.

5 | Discussion

The findings of this study demonstrate that subjectivity in social sustainability evaluations can be significantly reduced through the application of data-driven methodologies, as implemented in the revised SO-LCA model. Traditional approaches, such as Social Return on Investment (SROI) or Social Impact Assessment (SIA), often rely heavily on qualitative data and expert judgment, leading to variability and limited comparability across contexts. In contrast, the SO-LCA model introduces quantitative techniques, including Principal Component Analysis (PCA) and sigmoid normalization, to standardize and analyze social indicators more objectively and reproducibly.

This methodological shift addresses the longstanding challenge of inconsistency in conventional models by promoting replicability and cross-context comparability. Furthermore, the integration of machine learning elements and normalization algorithms enhances the model's ability to minimize bias, offering a more accurate, transparent, and reliable assessment of social impacts. These findings support the argument that quantitative methods are essential to improving the credibility and scientific rigor of social sustainability assessments in Industry 5.0 environments.

The Industry 5.0 paradigm, with its emphasis on human-centric innovation and technological integration, offers a compelling framework for advancing transparency and accountability in social sustainability. The SO-LCA model is fully aligned with this paradigm, leveraging real-time monitoring capabilities and data integration to ensure comprehensive evaluations of social performance. Technologies such as the Internet of Things (IoT) and blockchain can be integrated into the model to enhance traceability across the supply chain, enabling organizations to measure and report social impacts consistently and reliably.

These technological advancements directly address the shortcomings of earlier methodologies, providing stakeholders with actionable insights based on real-time, verifiable data. Moreover, the model's compatibility with evolving regulatory frameworks, such as the EU Corporate Sustainability Reporting Directive (CSRD), positions it as a valuable tool for both legal compliance and stakeholder trust-building. By demonstrating accountability, companies can strengthen their ESG credentials and align more effectively with societal expectations. The integration of Industry 5.0 technologies and the SO-LCA model thus bridges critical gaps in transparency and facilitates more effective ESG strategies.

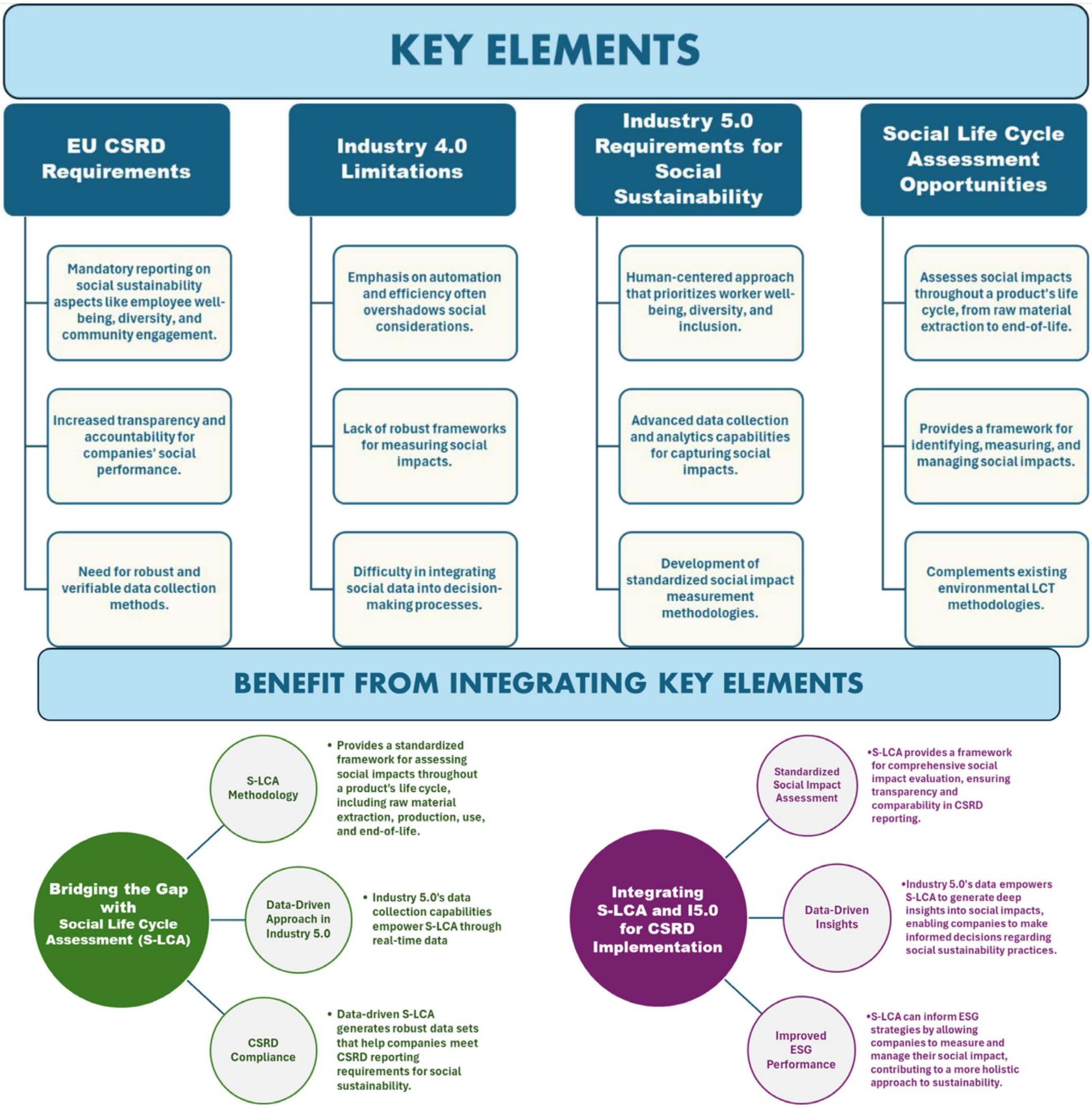

FIGURE 2 | Conceptual framework for implementing the EU CSRD in industry 5.0 with a focus on social sustainability.

A comparative analysis between the SO-LCA model and more traditional methodologies, such as SROI, highlights the limitations of relying predominantly on subjective evaluations and static reporting tools. Although SROI can yield insights into social value creation, its qualitative foundation often results in inconsistent applications and outcomes. The SO-LCA model addresses these limitations by incorporating advanced analytics and standardized procedures, enabling scalability, replicability, and data-driven decision-making.

Additionally, existing literature has emphasized the difficulty of reconciling detailed social reporting with accessibility for stakeholders. The SO-LCA model mitigates this by offering dynamic dashboards that transform complex data into intuitive visualizations, enhancing usability without sacrificing analytical depth. These innovations not only increase the practical applicability of the model but also respond to the demands of Industry 5.0, where transparency, real-time feedback, and technological integration are central to sustainable business practice.

6 | Conclusions

The findings of this research emphasize the strategic importance of integrating a mixed-method approach into the current SO-LCA model by combining expert consultation with PCA and Sigmoid Normalization techniques. Compared to conventional methods, this integration enhances the model's ability to offer a more comprehensive and objective evaluation of social indicators, improving both transparency and accountability. By merging qualitative insights with advanced quantitative techniques, this methodology strengthens the accuracy, reliability, and replicability of assessments. It also delivers a more granular understanding of social impacts, which is essential for informed decision-making in a complex, data-driven market. Specifically, in the context of Industry 5.0, the study highlights the transformative potential of a data-driven Social Organizational Life Cycle Assessment (SO-LCA) in fostering social sustainability. The integration of SO-LCA into organizational decision-making frameworks reinforces ESG compliance, supports transparency, and enables a systematic approach to social responsibility. In this respect, SO-LCA allows companies to identify areas requiring social transformation, strengthen their ESG performance, and align operational strategies with long-term sustainability goals. This integration also enhances corporate positioning in the ESG investment landscape by demonstrating measurable commitment to social performance.

From a theoretical standpoint, this study contributes to the literature on social sustainability assessment by advancing the SO-LCA methodology in three key ways. First, it addresses a significant gap by incorporating quantitative methods, such as PCA and sigmoid normalization, into a framework traditionally dominated by qualitative and subjective assessments. In doing so, the research supports calls for greater methodological rigor (Díaz-Reza et al. 2024; Singh and Cohen 2025) and offers a replicable and standardized approach to improve comparability across organizations. Second, the study contextualizes SO-LCA within the evolving Industry 5.0 paradigm, providing theoretical insight into how human-centric, digitally enabled manufacturing systems can operationalize social responsibility. Third, the proposed framework builds a conceptual bridge between Industry 5.0 principles and the European CSRD regulatory mandates, promoting not only regulatory compliance but also a shift toward more responsible and adaptive business practices.

From a managerial perspective, the study offers actionable guidance for companies aiming to align their operations with economic, social, and environmental sustainability objectives. It demonstrates how Business Intelligence (BI) platforms can incorporate objective social sustainability criteria through the application of data-driven SO-LCA. This allows organizations to integrate social data into strategic decision-making, facilitate organizational change, and strengthen overall sustainability performance. The integration of SO-LCA into existing Enterprise Resource Planning (ERP) systems further enables real-time social performance monitoring, supporting evidence-based decisions and improving ESG alignment. Moreover, by leveraging the vast volume of social data generated by Industry 5.0 operations (e.g., safety records, employee surveys, and supplier audits), companies can conduct in-depth analyses of value chain impacts. For example, by using supplier-related indicators—such as ethical compliance, local sourcing, or workforce innovation—firms can enhance supply chain responsibility and transparency. The SO-LCA model also facilitates CSRD compliance through the adoption of normalized and weighted indicators and transparent aggregation methods, resulting in audit-ready social sustainability reports that strengthen both regulatory alignment and stakeholder trust. In this way, the proposed data-driven SO-LCA framework offers an effective tool for improving ESG strategy execution by identifying priority areas, ensuring operational alignment with social responsibility goals, and providing granular insights into supply chain performance.

Despite its contributions, this study has several limitations that open avenues for future research. First, the focus on a single case study within the ceramic industry restricts generalizability. Sector-specific social dynamics may differ in healthcare, energy, or services, and future research should test this methodology across other industries. Second, reliance on a single firm limits external validity. Multiple case studies would enhance the robustness and transferability of findings. Third, while the study integrates expert judgment to address data limitations, it still introduces a degree of subjectivity. Future research could involve systematic primary data collection using real-time technologies such as IoT monitoring and digital supply chain analytics, alongside the development of an open-access social indicator database for benchmarking. Fourth, since the methodology has been applied to a large firm, future studies should explore its adaptability to SMEs, assessing scalability, cost-effectiveness, and operational feasibility in small-scale contexts. Additionally, research should investigate the development of a common unit of measurement to integrate social impact metrics with environmental, economic, and technological indicators under the broader Life Cycle Thinking framework. Future studies may also examine how emerging technologies such as blockchain and AI can improve traceability, data reliability, and transparency in social reporting. Another promising direction would be a comparative analysis of how companies are implementing the CSRD to identify best practices, challenges, and regulatory implications for advancing social sustainability.

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